

Constraining the Dark Universe

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We combine complementary datasets to constrain dark energy. Using standard Big Bang Nucleosynthesis and the observed abundances of primordial nuclides to put constraints on Ω_Q at temperatures near $T \sim 1\text{MeV}$, we find the strong constraint $\Omega_Q(\text{MeV}) < 0.045$ at 2σ c.l.. Under the assumption of flatness, using results from Cosmic Microwave Background (CMB) anisotropy measurements, high redshift supernovae (SN-Ia) observations and data from local cluster abundances we put a new constraint on the equation of state parameter $w_Q < -0.85$ at 68% c.l..

Introduction. The discovery that the universe's evolution may be dominated by an effective cosmological constant [1], is one of the most remarkable cosmological findings of recent years. An exceptional opportunity is now opening up to decipher the nature of dark matter [2], to test the veracity of theories and reconstruct the dark matters profile using a wide variety of observations over a broad redshift range.

One candidate that could possibly explain the observations is a dynamical scalar “quintessence” field. One of the strong aspects of quintessence theories is that they go some way explaining the fine-tuning problem, why the energy density producing the acceleration is $\sim 10^{-120} M_{pl}^4$. A vast range of “tracker” (see for example [3,11]) and “scaling” (for example [12]-[15]) quintessence models exist which approach attractor solutions, giving the required energy density, independent of initial conditions. The common characteristic of quintessence models is that their equations of state, $w_Q = p/\rho$, vary with time whilst a cosmological constant remains fixed at $w_Q = -1$. Observationally distinguishing a time variation in the equation of state or finding w_Q different from -1 will therefore be a success for the quintessential scenario.

We will here discuss observational constraints on general quintessence models.

In [23] we used standard big bang nucleosynthesis and the observed abundances of primordial nuclides to put constraints on the amplitude of the energy density, Ω_Q , at temperatures near $T \sim 1\text{MeV}$. The inclusion of a scaling field increases the expansion rate of the universe, and changes the ratio of neutrons to protons at freeze-out and hence the predicted abundances of light elements.

In [24] we have then combined the latest observations of the Cosmic Microwave Background (CMB) anisotropies provided by the Boomerang [16], DASI [17] and Maxima [18] experiments and the information from Large Scale Structure (LSS) with the luminosity distance of high redshift supernovae (SN-

Ia) to put constraints on the dark energy equation of state parameterized by a redshift independent quintessence-field pressure-to-density ratio w_Q . We also made use of the Hubble Space Telescope (HST) constraint on the Hubble parameter $h = 0.72 \pm 0.08$ [19].

We will briefly review the results obtained in those paper in the next sections.

Early-Universe Constraints from BBN. In the last few years important experimental progress has been made in the measurement of light element primordial abundances. For the ^4He mass fraction, Y_{He} , two marginally compatible measurements have been obtained from regression against zero metallicity in blue compact galaxies. A low value $Y_{\text{He}} = 0.234 \pm 0.003$ [5] and a high one $Y_{\text{He}} = 0.244 \pm 0.002$ [6] give realistic bounds. We use the high value in our analysis; if one instead considered the low value, the bounds obtained would be even stronger.

Observations in different quasar absorption line systems give a relative abundance of deuterium, which is critical in fixing the baryon fraction, of $D/H = (3.0 \pm 0.4) \cdot 10^{-5}$ [7].

In the standard BBN scenario, the primordial abundances are a function of the baryon density $\eta \sim \Omega_b h^2$ only. In order to put constraints on the energy density of a primordial field at $T \sim \text{MeV}$, we modified the standard BBN code [4] by including the quintessence energy component Ω_Q . We then performed a likelihood analysis in the parameter space $(\Omega_b h^2, \Omega_Q^{BBN})$ using the observed abundances Y_{He} and D/H . In Fig. 1 we plot the 1, 2 and 3σ likelihood contours in the $(\Omega_b h^2, \Omega_Q^{BBN})$ plane.

Our main result is that the experimental data for ^4He and D does not favour the presence of a dark energy component, providing the strong constraint $\Omega_Q(\text{MeV}) < 0.045$ at 2σ (corresponding to $\lambda > 9$ for the exponential potential scenario), strengthening significantly the previous limit of [8,15] $\Omega_Q(\text{MeV}) < 0.2$. The reason for the difference is due to the improvement in the measurements of the observed

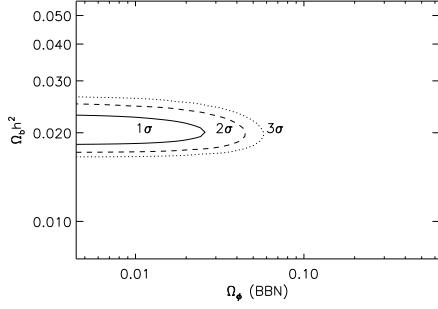


Figure 1. 1, 2 and 3 σ likelihood contours in the $(\Omega_b h^2, \Omega_Q(1\text{MeV}))$ parameter space derived from ${}^4\text{He}$ and D abundances.

abundances, especially for the deuterium, which now corresponds to approximately $\Delta N_{\text{eff}} < 0.2 - 0.3$ additional effective neutrinos (see, e.g. [9]), whereas Ref. [8,15] used the conservative value $\Delta N_{\text{eff}} < 1.5$. One could worry about the effect of any underestimated systematic errors, and we therefore multiplied the error-bars of the observed abundances by a factor of 2. Even taking this into account, there is still a strong constraint $\Omega_Q(\text{MeV}) < 0.09$ ($\lambda > 6.5$) at 2σ .

Constraints on the Dark energy equation of state.

The importance of combining different data sets in order to obtain reliable constraints on w_Q has been stressed by many authors (see e.g. [20], [21],[22]), since each dataset suffers from degeneracies between the various cosmological parameters and w_Q . Even if one restricts consideration to flat universes and to a value of w_Q constant in time then the SN-Ia luminosity distance and position of the first CMB peak are highly degenerate in w_Q and Ω_Q , the energy density in quintessence.

The effects of varying w_Q on the angular power spectrum of the CMB anisotropies can be reduced to just two. Firstly, since the inclusion of quintessence changes the overall content of matter and energy, the angular diameter distance of the acoustic horizon size at recombination will be altered. In flat models (i.e. where the energy density in matter is equal to $\Omega_M = 1 - \Omega_Q$), this creates a shift in the peak positions of the angular spectrum as

$$\begin{aligned} \mathcal{R} &= \sqrt{(1 - \Omega_Q)y}, \\ y &= \int_0^{z_{\text{dec}}} [(1 - \Omega_Q)(1 + z)^3 \\ &\quad + \Omega_Q(1 + z)^{3(1+w_Q)}]^{-1/2} dz. \end{aligned} \quad (1)$$

It is important to note that the effect is completely

degenerate in the interplay between w_Q and Ω_Q . Furthermore, it does not add any new features beyond those produced by the presence of a cosmological constant [25], and it is not particularly sensitive to further time dependencies of w_Q .

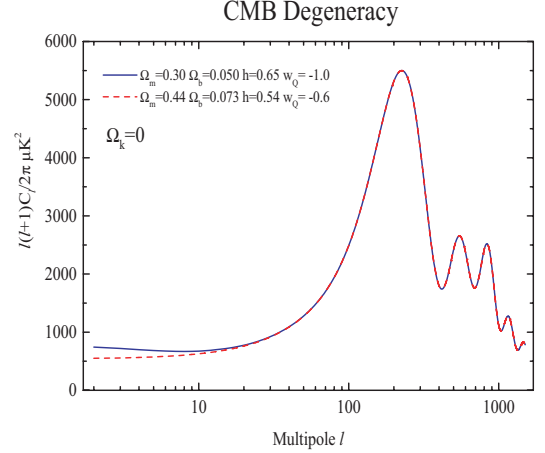


Figure 2. CMB power spectra and the angular diameter distance degeneracy. The models are computed assuming flatness, $\Omega_k = 1 - \Omega_M - \Omega_Q = 0$). The Integrated Sachs Wolfe effect on large angular scale slightly breaks the degeneracy. The degeneracy can be broken with a strong prior on h , in this paper we use the results from the HST.

Secondly, the time-varying Newtonian potential after decoupling will produce anisotropies at large angular scales through the Integrated Sachs-Wolfe (ISW) effect. The curve in the CMB angular spectrum on large angular scales depends not only on the value of w_Q but also its variation with redshift. However, this effect will be difficult to disentangle from the same effect generated by a cosmological constant, especially in view of the affect of cosmic variance and/or gravity waves on the large scale anisotropies.

In order to emphasize the importance of degeneracies between all these parameters while analyzing the CMB data, we plot in Figure 2 some degenerate spectra, obtained keeping the physical density in matter $\Omega_M h^2$, the physical density in baryons $\Omega_b h^2$ and \mathcal{R} fixed. As we can see from the plot, models degenerate in w_Q can easily be constructed. However the combination of CMB data with other different datasets can break the mentioned degeneracies.

Type Ia supernovae, in particular, can be extremely useful in this. Evidence that the universe's expansion rate was accelerating was first provided by

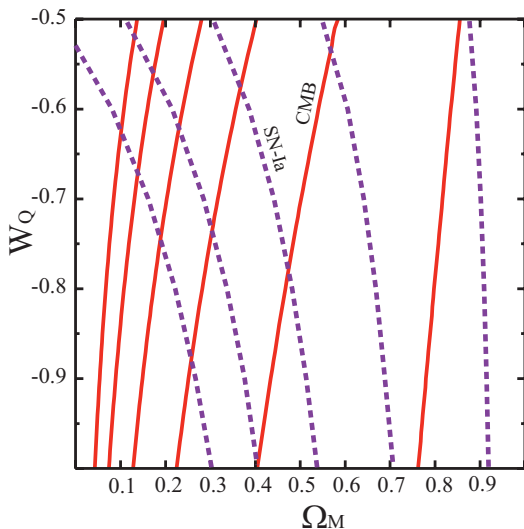


Figure 3. Contours of constant \mathcal{R} (CMB) and $SN-Ia$ luminosity distance in the $w_Q - \Omega_M$ plane. The degeneracy between the two distance measures can be broken by combining the two sets of complementary information. The luminosity distance is chosen to be equal to d_l at $z = 1$ for a fiducial model with $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$, $h = 0.65$. (We note that as $\Omega_Q = 1 - \Omega_M$ goes to zero the dependence of \mathcal{R} and d_L upon w_Q also become zero, as there is no dark energy present.) Figure taken from [24]

two groups, the SCP and High-Z Search Team([1]) using type Ia supernovae (SN-Ia) to probe the nearby expansion dynamics. SN-Ia seem to be good standard candles, as they exhibit a strong phenomenological correlation between the decline rate and peak magnitude of the luminosity. The observed apparent bolometric luminosity is related to the luminosity distance, measured in Mpc, by $m_B = M + 5 \log d_L(z) + 25$, where M is the absolute bolometric magnitude. The luminosity distance is sensitive to the cosmological evolution through an integral dependence on the Hubble factor $d_l = (1 + z) \int_0^z (dz'/H(z', \Omega_Q, w_q))$, and can therefore be used to constrain the scalar equation of state. As can be seen in Figure 3 there is an inherent degeneracy in the luminosity distance in the Ω_M/w_Q plane; one can see that little can be said about the equation of state from luminosity distance data alone. However, the degeneracies of CMB and SN1a data complement one another so that together they offer a more powerful approach for constraining w_Q .

Table I shows the $1-\sigma$ constraints on w_Q for different combinations of priors, obtained in [24] af-

Table 1

Constraints on w_Q and $\Omega_M = 1 - \Omega_Q$ using different priors and datasets. We always assume flatness and $t_0 > 10$ Gyr. The 1σ limits are found from the 16% and 84% integrals of the marginalized likelihood. The HST prior is $h = 0.72 \pm 0.08$ while for the BBN prior we use the conservative bound $\Omega_b h^2 = 0.020 \pm 0.005$.

CMB+HST	$w_Q < -0.62$ $0.15 < \Omega_M < 0.45$
CMB+HST+BBN	$-0.95 < w_Q < -0.62$ $0.15 < \Omega_M < 0.42$
CMB+HST+SN-Ia	$-0.94 < w_Q < -0.74$ $0.16 < \Omega_M < 0.34$
CMB+HST+SN-Ia+LSS	$w_Q < -0.85$ $0.28 < \Omega_M < 0.43$

ter marginalizing over all remaining *nuisance* parameters. The analysis is restricted to *flat* universes. One can see that w_Q is poorly constrained from CMB data alone, even when the strong HST prior on the Hubble parameter, $h = 0.72 \pm 0.08$, is assumed. Adding a Big Bang Nucleosynthesis prior, $\Omega_b h^2 = 0.020 \pm 0.005$, has small effect on the CMB+HST result. Adding SN-Ia breaks the CMB $\Omega_Q - w_Q$ degeneracy and improves the upper limit on w_Q , with $w_Q < -0.74$. Finally, including information from local cluster abundances through $\sigma_8 = (0.55 \pm 0.1)\Omega_M^{-0.5}$, where σ_8 is the *rms* mass fluctuation in spheres of $8h^{-1}$ Mpc, further breaks the quintessential-degeneracy, giving $w_Q < -0.85$ at $1-\sigma$. Also reported in Table I, are the constraints on Ω_M . As we can see, the combined data suggests the presence of dark energy with high significance, even in the case CMB+HST. It is interesting to project our likelihood in the $\Omega_Q - w_Q$ plane. Proceeding as in [27], we attribute a likelihood to a point in the (Ω_M, w_Q) plane by finding the remaining parameters that maximize it. We then define our 68%, 95% and 99% contours to be where the likelihood falls to 0.32, 0.05 and 0.01 of its peak value, as would be the case for a two dimensional multivariate Gaussian. In Figure 4 we plot likelihood contours in the (Ω_M, w_Q) plane for the joint analyses of CMB+SN-Ia+HST+LSS data together with the contours from the SN-Ia dataset only. As we can see, the combination of the data breaks the luminosity distance degeneracy.

Conclusions.

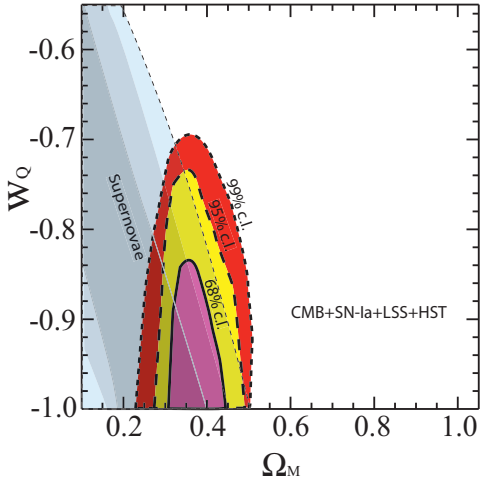


Figure 4. The likelihood contours in the (Ω_M, w_Q) plane, with the remaining parameters taking their best-fitting values for the joint CMB+SN-Ia+LSS analysis described in the text. The contours correspond to 0.32, 0.05 and 0.01 of the peak value of the likelihood, which are the 68%, 95% and 99% confidence levels respectively.

We have provided new constraints on the dark energy by combining different cosmological data. We have examined BBN abundances in a cosmological scenario with a scaling field. We have quantitatively discussed how large values of the fractional density in the scaling field Ω_Q at $T \sim 1\text{MeV}$ can be in agreement with the observed values of ^4He and D , assuming standard Big Bang Nucleosynthesis. The 2σ limit $\Omega_Q(1\text{MeV}) < 0.045$ severely constrains a wide class of quintessential scenarios, like those based on an exponential potential. For example, for the pure exponential potential the total energy today is restricted to $\Omega_Q = \frac{3}{4}\Omega_Q(1\text{MeV}) \leq 0.04$. This result put strong constraints on the presence of quintessence during recombination.

We have then provided constraints on the equation of state parameter w_Q . The new CMB results provided by Boomerang and DASI improve the constraints from previous and similar analysis (see e.g., [20],[28]), with $w_Q < -0.85$ at 68% c.l. ($w_Q < -0.76$ at 95% c.l.). We have also demonstrated how the combination of CMB data with other datasets is crucial in order to break the $\Omega_Q - w_Q$ degeneracy. The constraints from each single datasets are, as expected, quite broad but compatible with each other, providing an important consistency test. When comparison is possible (i.e. restricting to similar priors

and datasets), our analysis is compatible with other recent analysis on w_Q ([30]). Our final result is perfectly in agreement with the $w_Q = -1$ cosmological constant case and gives no support to a quintessential field scenario with $w_Q > -1$. A frustrated network of domain walls or a purely exponential scaling field are excluded at high significance. In addition a number of quintessential models are highly disfavored, e.g. power law potentials with $p \geq 1$ and the oscillatory potential, to name a few.

It will be the duty of higher redshift datasets, for example from clustering observations [29] to point to a variation in w that might place quintessence in a more favorable light.

The result obtained here, however, could be plagued by some of the theoretical assumptions we made. The CMB and LSS constraints can be weakened by the inclusion of additional relativistic degrees of freedom [33], by a background of gravity waves, of isocurvature perturbations or by adding features in the primordial perturbation spectra. These modifications are not expected in the most basic and simplified inflationary scenario but they are still compatible with the present data. The SN-Ia result has been obtained under the assumption of a constant-with-time $w_Q > -1$. Inclusion of the region with $w_Q < -1$ could affect our constraints ([32]). In [24] we have shown that in general w_{eff} is a rather good approximation for dynamical quintessential models since the luminosity distance depends on w_Q through a multiple integral that smears its redshift dependence, and our results are therefore valid for a wide class of quintessential models. This ‘numbering’ of sensitivity to w_Q , first noticed by [31], implies that maybe an effective equation of state is the most tangible parameter able to be extracted from supernovae. However with the promise of large data sets from Planck and SNAP satellites, opportunities may yet still be open to reconstruct a time varying equation of state [22].

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